

Hybrid Grey Wolf and Finite Element Method (GWO-FEM) Algorithm for Enhancing High Voltage Insulator String Performance in Wet Pollution Conditions

Dyhia Doufene

Department of Electrical Engineering
Electrical and Industrial System Laboratory (LSEI)
University of Science and Technology Houari Boumediene
Bab Ezzouar, Algeria
doufenedyhia@yahoo.fr

Samira Benharat

Department of Electrical Engineering
Electrical and Industrial System Laboratory (LSEI)
University of Science and Technology Houari Boumediene
Bab Ezzouar, Algeria
sbenharat@hotmail.fr

Slimane Bouazabia

Department of Electrical Engineering
Electrical and Industrial System Laboratory (LSEI)
University of Science and Technology Houari Boumediene
Bab Ezzouar, Algeria
sbouazabia@yahoo.fr

Sid Ahmed Bessedik

Department of Electrical Engineering
Université Amar Telidji de Laghouat
Laghouat, Algeria
s.bessedik@lagh-univ.dz

Received: 12 April 2022 | Revised: 29 April 2022, 3 May 2022, and 7 May 2022 | Accepted: 12 May 2022

Abstract- The presence of wet pollution on the upper surface of a string insulator increases the electric field on the insulator surface, especially at the triple junction (pin-cement, cement-porcelain) as well as at the surrounding air of the insulator. The rise of the electric field leads to the ionization of the air surrounding the insulator. This phenomenon, called corona discharge, is accompanied by several consequences that are harmful to the electricity transmission network, such as electromagnetic interferences, energy losses, visible light, audible noise, and the destruction of materials by erosion. If favorable conditions are gathered, it may even cause the flashover of the insulator. Designing an optimal insulator shape that reduces this electric field value at the triple junction will be an important achievement in enhancing the performance of electrical grids. The objective of this paper is to evolve a hybrid algorithm based on the GWO-FEM for optimizing the shape and the electrical performance of a string insulator. To achieve this purpose, this work is structured in four parts. First, modeling of the insulator string geometry is conducted in Comsol-multiphysics, then FEM computation of the electric field on the polluted surface of the string insulator is completed, and the maximum electric field value at the triple junction is saved as the fitness function that will be sent to the GWO algorithm to be optimized (minimized). The third part of the work is devoted to the coding of the constrained (electrical and geometrical constraints) GWO algorithm in a Matlab interface, and finally, coupling the GWO code with the FEM code. This study is achieved in wet polluted conditions. The results are given in both 2D and 3D representations. From the obtained results we can confirm that

the developed GWO-FEM hybrid algorithm for optimizing insulator strings is a very promising tool for designing and enhancing the shape and the electrical performance of insulators.

Keywords- insulator design; grey wolf optimisation; finite element method; 3D electric field

I. INTRODUCTION

Transmission and distribution lines constitute the link between production and consumers. These lines are held by insulating strings [1]. Their performance is crucial for the good functioning of the electrical network. It is well established by experimental studies and confirmed by simulations [2-8], that the highest electric field value around an insulating string is found on the last pin in contact with the high voltage conductor, more exactly at the triple junction (pin-cement, cement-porcelain), which also corresponds to the highest thermal point [9], therefore, these areas are very critical in high voltage lines. The presence of high electric field leads to corona discharges by ionizing the surrounding air of the insulator, resulting in energy losses, electromagnetic interferences, visible light, audible noise, and the destruction of materials by erosion [10-12]. When the electric field stress exceeds a threshold value, especially in the presence of pollution conditions [13], flashover of the insulator string may occur. Thus, finding the insulating string design that can reduce the critical value of the electric field at the triple junction region, and at the same time reduce the weight of the insulator

constitutes, a considerable advantage for improving the performance of electrical networks. It is here where the contribution of the present paper is registered.

Designing an improved shape of the insulator string involves taking into account many constraints, such as electrical, mechanical, environmental and economic, so using simulations prior to real testing and manufacturing is money and time saving. Recent works carried out concerning the improvement of the high voltage insulators performance based on optimization methods, are divided into two main categories: (i) optimizing the shape of the chain elements [14-23] and (ii) grading ring optimization [24-25]. This research aims to study a hybrid algorithm based on the Grey Wolf Optimization and the Finite Element Method (GWO-FEM) for designing an insulator sting and enhancing its electrical and geometrical performance. The current paper brings a complementarity to fill some existing gaps in the field of designing high voltage insulators. Its main contributions are:

- The proposal of the new hybrid GWO-FEM algorithm for insulator optimization.
- Corona ring optimization and one-element insulator optimization have been already done in previous studies, but, to the best of our knowledge, total string optimization is achieved for the first time in this paper.
- By using optimization constraints, two goals are achieved, namely reduction of the electric field value at the triple junction and of the weight of the insulator string.
- 3D geometry representation and electric field distribution were conducted.
- The most significant contribution of this work is the pollution case study which is conducted for the first time in this paper.

To accomplish the above contributions, this work is divided into four main parts:

- Modeling of the insulator string geometry in Comsol-multiphysics.
- FEM computation of the electric field on the insulation surface of the insulator and saving the maximum electric field value at the triple junction as the fitness function that will be sent to the GWO algorithm to be optimized.
- Coding of the constrained GWO algorithm in Matlab [26-27].
- Coupling of the GWO code with the FEM code.

II. INSULATOR GEOMETRY MODELING

Figure 1 shows one element of the studied 6-element string insulator. The parameters of the insulators are given in Table I. The model is a string insulator of 6 elements of an U400B glass insulator commonly used in the Algerian power grid. The modeling of the insulator geometry in Comsol-multiphysics is represented in 2D and 3D in Figure 2.

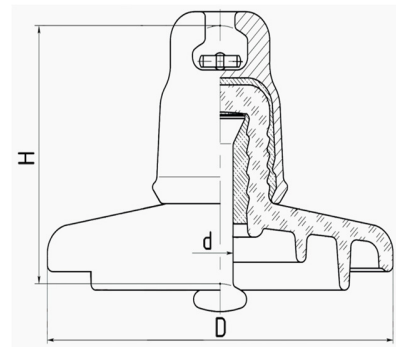


Fig. 1. U400B model.

TABLE I. PARAMETERS OF THE INSULATOR STRING

Dimensions [cm]			Applied voltage [kV]	
Shed diameter (D)	Unit spacing (H)	Creepage distance (L)	Pin	Cap
32.0	20.5	435	100	0

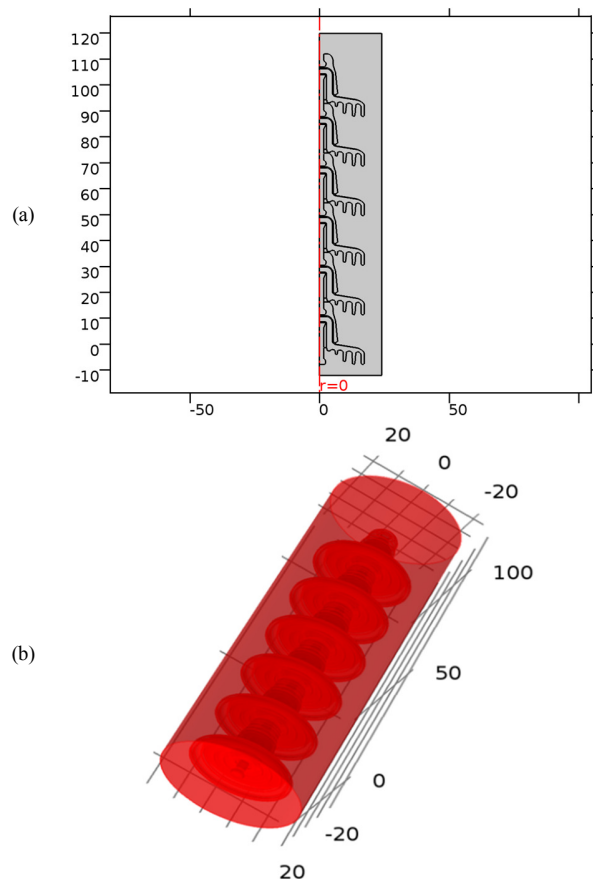


Fig. 2. The reference 6-element string insulator. (a) 2D, (b) 3D.

A wet pollution layer (Figure 3) is put on the upper surface of each element of the string. The thickness of the pollution layer is 0.5mm. The pollution layer is in contact with the earthed cap. The material parameters used for the simulation are given in Table II.

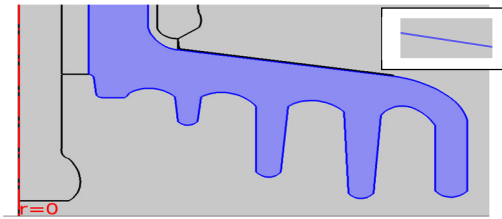


Fig. 3. Zoom in the pollution layer.

TABLE II. MATERIAL PARAMETERS OF THE SIMULATION MODEL

Material	Permittivity	Conductivity [S/m]
Air	1	0
Glass	5.59	10-14
Iron	106	5,998.107
Cement	5.9	10-12
Pollution	80	10-4

III. FEM COMPUTATION OF POTENTIAL AND ELECTRIC FIELD

After the meshing process, potential and electric field distributions are computed by solving (1) and (2) by using FEM.

$$\Delta V=0 \quad (1)$$

$$\vec{E} = -\vec{\nabla} V \quad (2)$$

where E represents the electric field and V is the electric potential.

The electric potential varies from 100kV from the pin to 0V on the cap as shown in Figure 4 giving the potential repartition along the creepage distance of the insulator string.

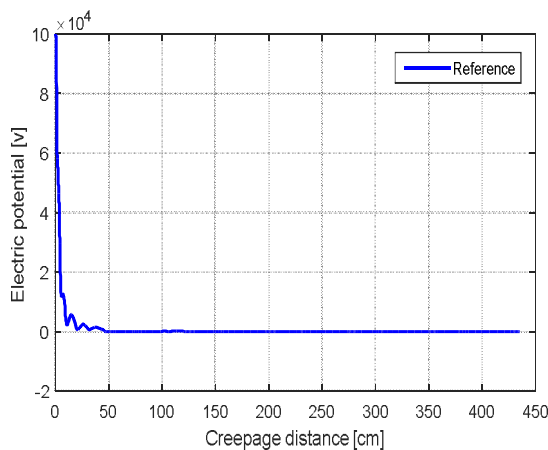


Fig. 4. Electric potential repartition on the creepage path of the insulator string.

From the electric field repartition (Figure 5), starting from the pin towards the cap, we record a maximum value of 190kV/cm at the last pin. This obtained result is in adequacy with the results from the literature review [2-9], which attest that the highest electric field value is located at the last pin of the string connected to the high voltage and exactly at the triple junction. So, for the optimization purpose, the maximum electric field E_{max} recorded at this triple junction is saved as the

fitness function and is sent to the GWO cod to be optimized (minimized). The potential and electric field distribution in 2D and 3D are given in Figures 6 and 7 respectively. A zoom in the last pin shows clearly the triple junction with the highest electric field value.

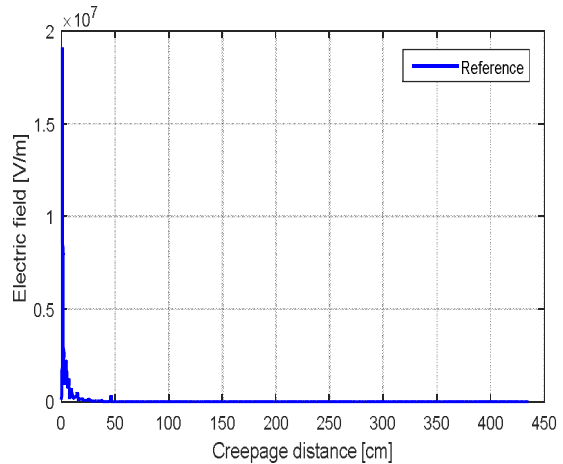


Fig. 5. Electric field repartition on the creepage path of the insulator string.

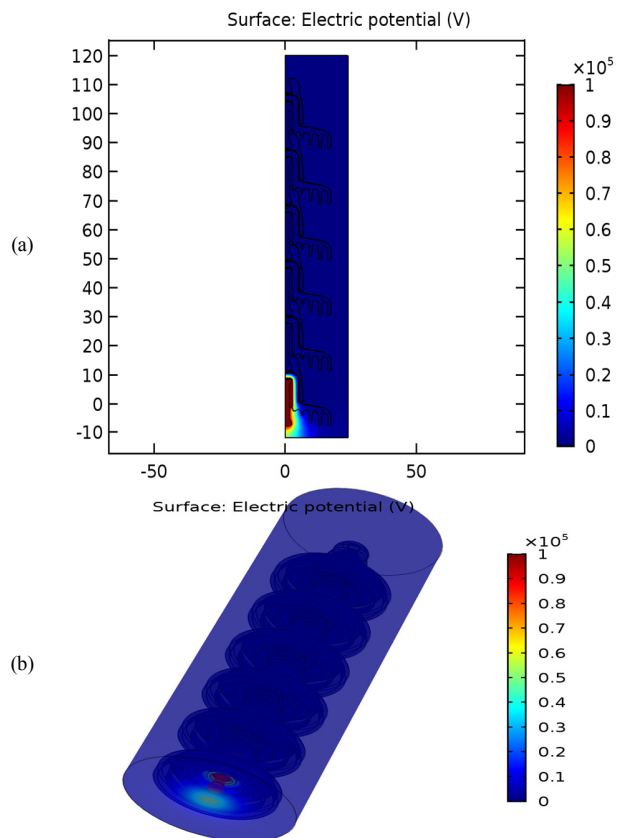


Fig. 6. Electric potential distribution for the insulator sting. a) 2D, (b) 3D.

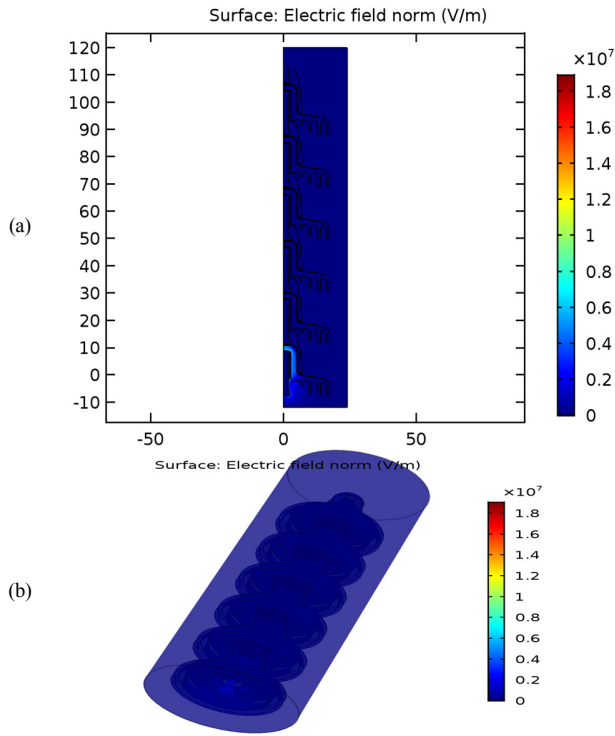


Fig. 7. Electric field distribution for the insulator sting. a) 2D, (b) 3D.

IV. OPTIMIZATION PROCESS USING GWO

The principle of the GWO algorithm [28] is based on reproducing the hunting technique of grey wolves and modeling mathematically their social hierarchy. Four categories can be noticed in wolf population. The α (alpha), β (beta), and δ (delta) wolves represent the optimal solutions for the optimization problem. The last category is the ω (omega) wolves, which are the followers [28, 30]. The mathematical modeling of the steps of the hunting process is given below.

- Encircling: (surrounding the prey while hunting), is modeled by (3) and (4):

$$\vec{D} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)| \quad (3)$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \quad (4)$$

where t is the current iteration, X_p and X are the positions of the prey and the grey wolf respectively, C and A are the coefficient vectors calculated by (5) and (6):

$$\vec{A} = 2 \cdot \vec{a}(t) \cdot \vec{r}_1 - \vec{a}(t) \quad (5)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \quad (6)$$

The elements of the vector a linearly decrease from 2 to 0, and r_1, r_2 are random vectors in $[0,1]$.

- Hunting: Equations (7)-(9) reproduce the hunting model:

$$\begin{cases} \vec{D}_\alpha = |\vec{C}_1 \cdot \vec{X}_\alpha - \vec{X}(t)| \\ \vec{D}_\beta = |\vec{C}_2 \cdot \vec{X}_\beta - \vec{X}(t)| \\ \vec{D}_\delta = |\vec{C}_3 \cdot \vec{X}_\delta - \vec{X}(t)| \end{cases} \quad (7)$$

where $C_1, C_2,$ and C_3 are obtained by (6).

$$\begin{cases} \vec{X}_1(t) = \vec{X}_\alpha - \vec{A}_1 \cdot (\vec{D}_\alpha(t)) \\ \vec{X}_2(t) = \vec{X}_\beta - \vec{A}_2 \cdot (\vec{D}_\beta(t)) \\ \vec{X}_3(t) = \vec{X}_\delta - \vec{A}_3 \cdot (\vec{D}_\delta(t)) \end{cases} \quad (8)$$

where $X_\alpha, X_\beta,$ and X_δ are the first three best solutions at iteration $t, A_1, A_2,$ and A_3 are obtained from (5), and $D_\alpha, D_\beta,$ and D_δ are obtained from (7).

$$\vec{X}(t+1) = \frac{\vec{X}_1(t) + \vec{X}_2(t) + \vec{X}_3(t)}{3} \quad (9)$$

- Attacking: when the prey representing the optimal solution, can no longer move, the wolves launch the attack, which marks the end of the hunt. This process is mathematically reproduced by decreasing the value of a linearly from 2 to 0.

V. GWO AND FEM COUPLING

The hybrid GWO-FEM algorithm is obtained by following the different steps given in the flowchart of Figure 8.

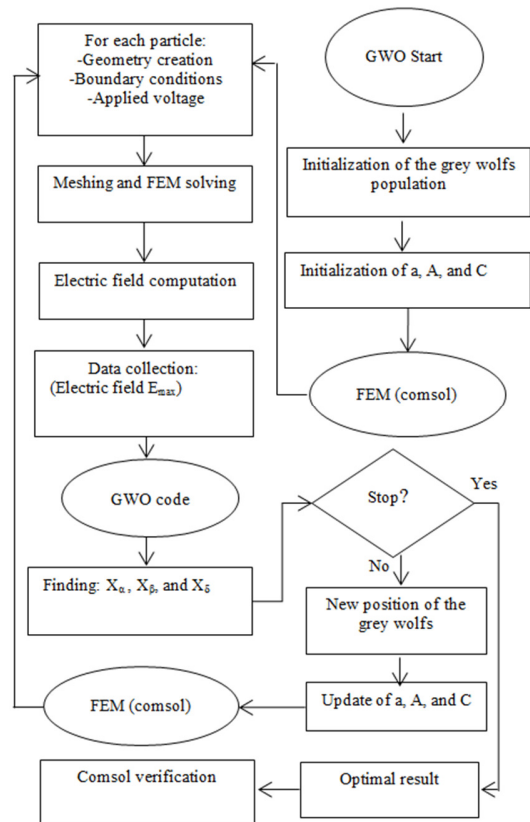


Fig. 8. Flowchart of the GWO-FEM algorithm process.

VI. OPTIMIZATION RESULTS

The different lengths (L_1 to L_4), shown in Figure 9 are taken as the optimization variables. A constraint is imposed to the total creepage length to not exceed the reference length of the

industrial model in order to obtain a shape with a reduced creepage distance and as a consequence reduced weight of the insulator. The stopping criterion of the hybrid algorithm is 150 iterations [15]. The obtained shape of the optimized insulator string is given in Figure 10. A comparative analysis of the results before and after optimization is established in Table III.

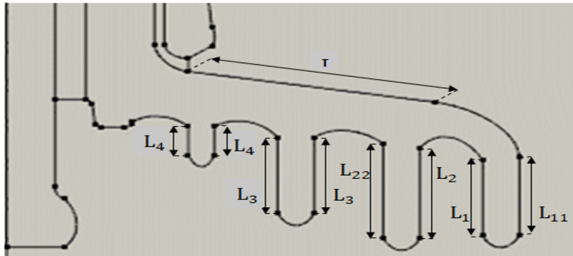


Fig. 9. The optimization variables.

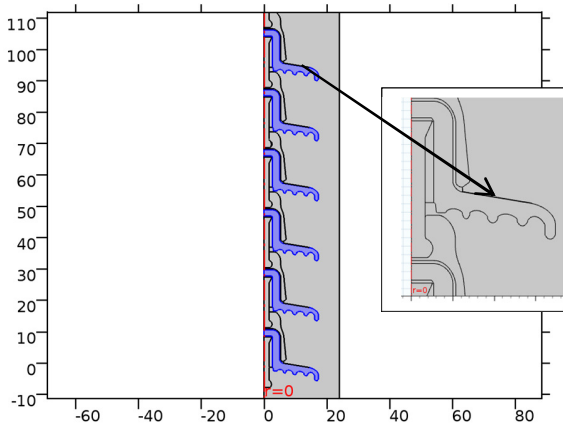


Fig. 10. Optimized shape of the string insulator.

TABLE III. OPTIMIZATION RESULTS

	Reference string	Optimized string
l_1 [cm]	3.30	0.50
l_{11} [cm]	3.40	0.60
l_2 [cm]	3.85	0.14
l_{22} [cm]	4.03	0.32
l_3 [cm]	3.50	0.130
l_4 [cm]	1.16	5
Creepage distance [cm]	435	324
Creepage length reduction (%)	25	
Electric field at the triple junction [kV/cm]	190	177
Electric field reduction at the triple junction region (%)	8	
The diametrical surface of the insulating glass surface [cm ²]	435.7	369.7
Reduction of the surface value of the insulating glass surface [%]	15.14	

The potential and the electric field distributions after optimization are given in Figures 11 and 12 respectively. The potential and electric field repartition along the creepage distance (from the pin to the cap) on the optimized insulator string are registered in Figures 13 and 14 respectively.

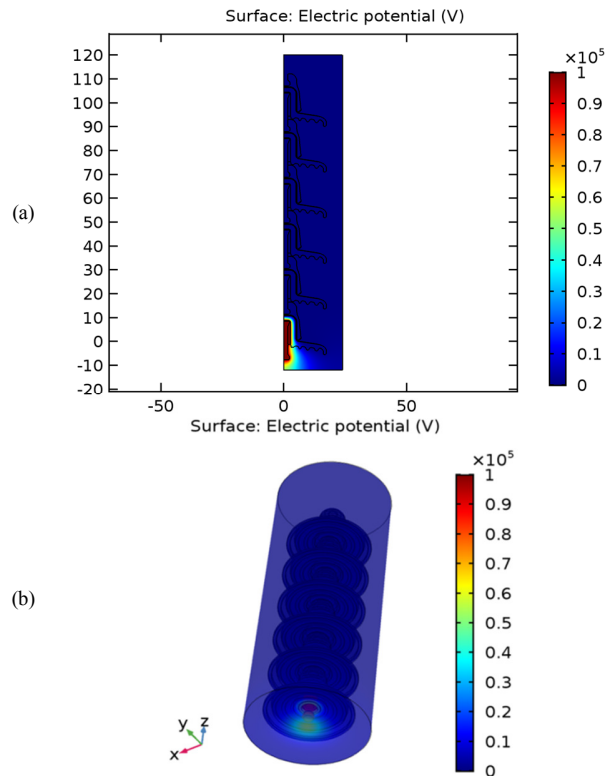


Fig. 11. Electric potential distribution for the optimized insulator sting. (a) 2D, (b) 3D.

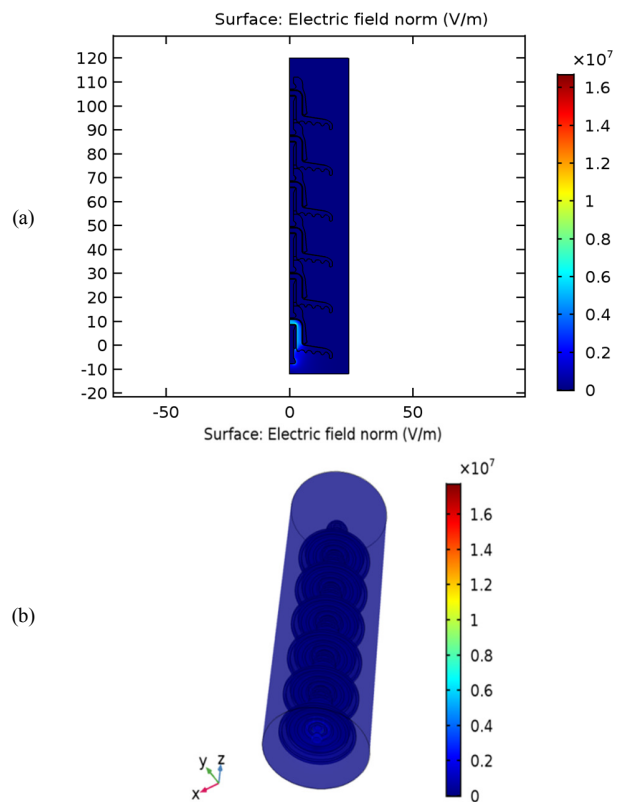


Fig. 12. Electric field distribution for the optimized insulator sting. (a) 2D, (b) 3D.

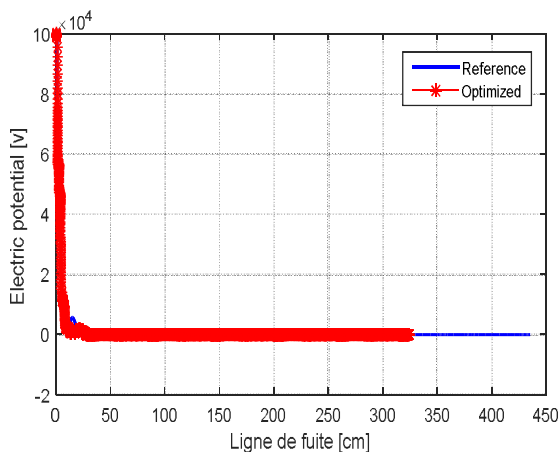


Fig. 13. Electric potential repartition on the creepage path of the optimized string insulator.

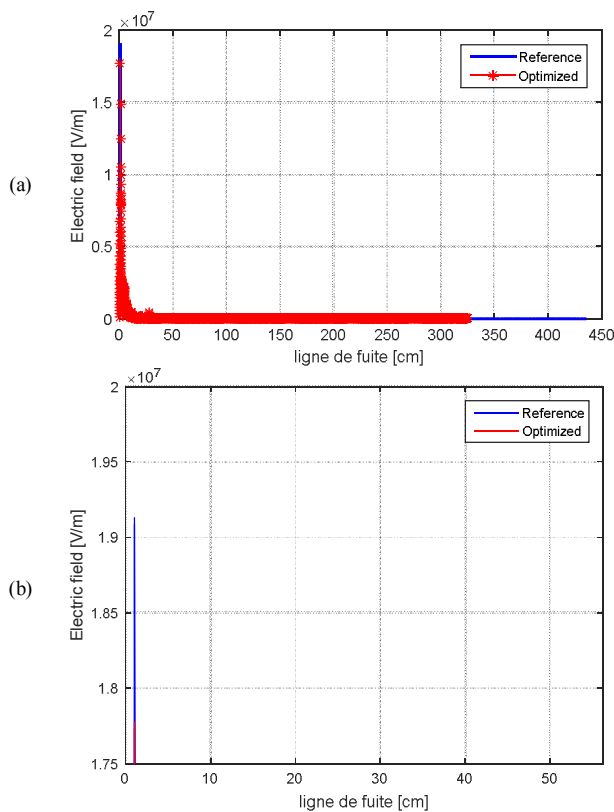


Fig. 14. Electric field repartition on the creepage path of the optimized string insulator. (a) On the creepage path (from the pin to the cap), (b) zoom at the triple junction point (the last pin connected to the high voltage).

VII. DISCUSSION

From the comparative analysis between the cases before and after optimization (Table III), we can clearly notice the efficiency of the proposed optimization method since the two objectives set in this work, namely the reduction of the electric field and the creepage distance, have been correctly achieved. The developed GWO-FEM hybrid algorithm for optimizing insulator strings is a promising technique for designing and

enhancing the shape and the electrical performance of insulators. The comparative analysis carried out between the reference string and the optimized one in the presence of a wet pollution shows the following findings :

- A decrease of 8% in the electric field at the triple junction of the last insulator connected to the high voltage was recorded. This reduction constitutes a major advantage with regard to the reduction of corona discharges at the surface of the insulator, and consequently a decline of the noise, the light, and the electromagnetic interferences issued from the ionization phenomenon of the air particles surrounding the insulator string. Other positive consequences are the elongation of the insulator lifetime following the reduction of the corrosive effect of the corona discharges and the reduced risk of insulator flashover.
- Creepage length decreased by 25% and the diametral surface of the string insulator by 15.14%, which represent a huge advantage resulting in an important weight decrease and thus improving the economic aspect of the manufacturing of the insulators.
- The 3D study gives a more realistic aspect to the achieved results.

Comparing the obtained results with [23, 24], where the objective function (the electric field at the pin region) is predicted using Artificial Neural Networks, big similarity in the obtained shape after optimization is noticed.

VIII. CONCLUSION

The developed GWO-FEM hybrid algorithm provides very satisfactory results, therefore it can be used as a powerful tool for designing high voltage insulators in general. With this hybrid algorithm, optimal design of the insulator string is reached, satisfying two constraints: an electrical constraint (minimizing the maximum electric field value) and a geometrical constraint (minimizing the weight of the insulator string). The main advantage of the proposed hybrid algorithm is the possibility of combining other constraints that are involved in the flashover of high voltage insulators, such as the dry band formation, NSDD encapsulation, water draining, and also mechanical and thermal stresses can be taken into account, which is possible with the use of the computation interface of Comsol-multiphysics that allows multiphysics studies at the same time and thus permitting the obtainment of an optimal design encompassing all the stresses undergone by the insulator string.

ACKNOWLEDGMENT

The authors would like to thank the Algerian Ministry of Higher Education and Scientific Research and the Directorate General for Scientific Research and Technological Development who provided the scholarship for visiting the high voltage laboratory at the School of Engineering at Cardiff University.

REFERENCES

- [1] D. Pylarinos and I. Pellas, "Investigation of an Insulator Flashover in an 150 kV OTL of the Power System of Crete," *Engineering, Technology &*

- Applied Science Research*, vol. 9, no. 5, pp. 4851–4858, Oct. 2019, <https://doi.org/10.48084/etasr.3198>.
- [2] E. Akbari, M. Mirzaie, M. B. Asadpoor, and A. Rahimnejad, "Effects of Disc Insulator Type and Corona Ring on Electric Field and Voltage Distribution over 230-kV Insulator String by Numerical Method," *Iranian Journal of Electrical and Electronic Engineering*, vol. 9, no. 1, pp. 44–57, Mar. 2013.
- [3] V. T. Kontargyri, I. F. Gonos, and I. A. Stathopoulos, "Measurement and simulation of the electric field of high voltage suspension insulators," *European Transactions on Electrical Power*, vol. 19, no. 3, pp. 509–517, 2009, <https://doi.org/10.1002/etep.238>.
- [4] A. J. Phillips *et al.*, "Electric Fields on AC Composite Transmission Line Insulators," *IEEE Transactions on Power Delivery*, vol. 23, no. 2, pp. 823–830, Apr. 2008, <https://doi.org/10.1109/TPWRD.2007.911127>.
- [5] T. Doshi, R. S. Gorur, and J. Hunt, "Electric field computation of composite line insulators up to 1200 kV AC," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 3, pp. 861–867, Jun. 2011, <https://doi.org/10.1109/TDEI.2011.5931075>.
- [6] Y. Qing, W. Sima, D. Jiazhao, Y. Tao, and C. Lin, "New optimization method on electric field distribution of composite insulator," in *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, West Lafayette, IN, Oct. 2010, pp. 1–4, <https://doi.org/10.1109/CEIDP.2010.5724046>.
- [7] Y. Zhang *et al.*, "Flashover Performance Test with Lightning Impulse and Simulation Analysis of Different Insulators in a 110 kV Double-Circuit Transmission Tower," *Energies*, vol. 11, no. 3, Mar. 2018, Art. no. 659, <https://doi.org/10.3390/en11030659>.
- [8] C. A. Christodoulou, V. Vita, V. Mladenov, and L. Ekonomou, "On the Computation of the Voltage Distribution along the Non-Linear Resistor of Gapless Metal Oxide Surge Arresters," *Energies*, vol. 11, no. 11, Nov. 2018, Art. no. 3046, <https://doi.org/10.3390/en11113046>.
- [9] D. Doufene, S. Bouazabia, and R. Bouhaddiche, "Heating Dissipation Study of a Pollution Layer on a Cap and Pin Insulator," in *International Conference on Communications and Electrical Engineering*, El Oued, Algeria, Dec. 2018, pp. 1–4, <https://doi.org/10.1109/CCEE.2018.8634549>.
- [10] O. G. Gryb, I. T. Karpaliuk, A. O. Zaporozhets, S. V. Shvets, and N. V. Rudevich, "Acoustic Diagnostics for Determining the Appearance of Corona Discharge," in *Control of Overhead Power Lines with Unmanned Aerial Vehicles (UAVs)*, Y. I. Sokol and A. O. Zaporozhets, Eds. New York, NY, USA: Springer, 2021, pp. 127–157.
- [11] I. O. Zaitsev and V. V. Kuchanskyy, "Corona Discharge Problem in Extra High Voltage Transmission Line," in *Systems, Decision and Control in Energy II*, A. Zaporozhets and V. Artemchuk, Eds. New York, NY, USA: Springer, 2021, pp. 3–30.
- [12] A. V. Golenishchev-Kutuzov, V. A. Golenishchev-Kutuzov, D. A. Ivanov, G. D. Mardanov, A. V. Semennikov, and Yu. V. Van'kov, "Complex Diagnostics of Defects in High-Voltage Insulators," *Bulletin of the Russian Academy of Sciences: Physics*, vol. 83, no. 12, pp. 1490–1493, Dec. 2019, <https://doi.org/10.3103/S1062873819120062>.
- [13] M. Dimitropoulou, D. Pylarinos, K. Siderakis, E. Thalassinakis, and M. Danikas, "Comparative Investigation of Pollution Accumulation and Natural Cleaning for Different HV Insulators," *Engineering, Technology & Applied Science Research*, vol. 5, no. 2, pp. 764–774, Apr. 2015, <https://doi.org/10.48084/etasr.545>.
- [14] S. F. Stefenon, C. S. Furtado Neto, T. S. Coelho, A. Nied, C. K. Yamaguchi, and K.-C. Yow, "Particle swarm optimization for design of insulators of distribution power system based on finite element method," *Electrical Engineering*, vol. 104, no. 2, pp. 615–622, Apr. 2022, <https://doi.org/10.1007/s00202-021-01332-3>.
- [15] D. Doufene, S. Bouazabia, S. A. Bessedik, and K. Ouzzir, "Grey Wolf Optimizer Algorithm for Suspension Insulator Designing," in *Sixth International Congress on Information and Communication Technology*, London, UK, Feb. 2021, pp. 763–771, https://doi.org/10.1007/978-981-16-2380-6_67.
- [16] K. Bhattacharya, S. Chakravorti, and P. K. Mukherjee, "Insulator contour optimization by a neural network," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 8, no. 2, pp. 157–161, Apr. 2001, <https://doi.org/10.1109/94.919908>.
- [17] W. Chen, H. Yang, and H. Huang, "Optimal Design of Support Insulators Using Hashing Integrated Genetic Algorithm and Optimized Charge Simulation Method," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 2, pp. 426–433, Apr. 2008, <https://doi.org/10.1109/TDEI.2008.4483461>.
- [18] W.-S. Chen, H.-T. Yang, and H.-Y. Huang, "Contour Optimization of Suspension Insulators Using Dynamically Adjustable Genetic Algorithms," *IEEE Transactions on Power Delivery*, vol. 25, no. 3, pp. 1220–1228, Jul. 2010, <https://doi.org/10.1109/TPWRD.2010.2046187>.
- [19] D. Doufene, S. Bouazabia, and A. Haddad, "Optimised performance of cap and pin insulator under wet pollution conditions using a mono-objective genetic algorithm," *Australian Journal of Electrical and Electronics Engineering*, vol. 16, no. 3, pp. 149–162, Jul. 2019, <https://doi.org/10.1080/1448837X.2019.1627740>.
- [20] S. Banerjee, A. Lahiri, and K. Bhattacharya, "Optimization of support insulators used in HV systems using support vector machine," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 14, no. 2, pp. 360–367, Apr. 2007, <https://doi.org/10.1109/TDEI.2007.344616>.
- [21] D. Doufene, S. Bouazabia, and A. Haddad, "Shape and electric performance improvement of an insulator string using particles swarm algorithm," *IET Science, Measurement & Technology*, vol. 14, no. 2, pp. 198–205, Dec. 2019, <https://doi.org/10.1049/iet-smt.2019.0405>.
- [22] D. Doufene, S. Bouazabia, A. A. Ladjici, and A. Haddad, "Polluted insulator optimization using neural network combined with genetic algorithms," in *18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering*, Lodz, Poland, Sep. 2017, pp. 1–2, <https://doi.org/10.1109/ISEF.2017.8090689>.
- [23] D. Doufene, S. Bouazabia, and A. A. Ladjici, "Shape optimization of a cap and pin insulator in pollution condition using particle swarm and neural network," in *5th International Conference on Electrical Engineering - Boumerdes*, Boumerdes, Algeria, Oct. 2017, pp. 1–4, <https://doi.org/10.1109/ICEE-B.2017.8192094>.
- [24] B. M'hamdi, M. Tegar, and A. Mekhaldi, "Optimal design of corona ring on HV composite insulator using PSO approach with dynamic population size," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 2, pp. 1048–1057, Apr. 2016, <https://doi.org/10.1109/TDEI.2015.005383>.
- [25] D. Nie, H. Zhang, Z. Chen, X. Shen, and Z. Du, "Optimization design of grading ring and electrical field analysis of 800 kV UHVDC Wall wall bushing," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 4, pp. 1361–1368, Aug. 2013, <https://doi.org/10.1109/TDEI.2013.6571457>.
- [26] D. Pylarinos, "A Custom-made MATLAB Based Software to Manage Leakage Current Waveforms," *Engineering, Technology & Applied Science Research*, vol. 1, no. 2, pp. 36–42, Apr. 2011, <https://doi.org/10.48084/etasr.31>.
- [27] G. Satheesh, B. Basavaraja, and P. M. Nirgude, "Electric Field Simulation Around Contaminated SIR Insulators Using MATLAB," *Engineering, Technology & Applied Science Research*, vol. 8, no. 1, pp. 2542–2545, Feb. 2018, <https://doi.org/10.48084/etasr.1742>.
- [28] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey Wolf Optimizer," *Advances in Engineering Software*, vol. 69, pp. 46–61, Mar. 2014, <https://doi.org/10.1016/j.advengsoft.2013.12.007>.
- [29] M. H. Nadimi-Shahraki, S. Taghian, and S. Mirjalili, "An improved grey wolf optimizer for solving engineering problems," *Expert Systems with Applications*, vol. 166, Mar. 2021, Art. no. 113917, <https://doi.org/10.1016/j.eswa.2020.113917>.
- [30] S. Arora, H. Singh, M. Sharma, S. Sharma, and P. Anand, "A New Hybrid Algorithm Based on Grey Wolf Optimization and Crow Search Algorithm for Unconstrained Function Optimization and Feature Selection," *IEEE Access*, vol. 7, pp. 26343–26361, 2019, <https://doi.org/10.1109/ACCESS.2019.2897325>.